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Key Points:
- This work describes problems found within long-term ionospheric records, likely caused by distributed storage system
- The problems found still persist, and there is no appearance of reparation
- Ionospheric data are valuable records of the behavior of the ionosphere, solar activity, and the entire Sun-Earth system

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Critical Issues in Ionospheric Data Quality and Implications for Scientific Studies

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Abstract Ionospheric data are valuable records of the behavior of the ionosphere, solar activity, and the entire Sun-Earth system. The data are critical for both societally important services and scientific investigations of upper atmospheric variability. This work investigates some of the difficulties and pitfalls in maintaining long-term records of geophysical measurements. This investigation focuses on the ionospheric parameters contained in the historical data sets within the National Oceanic and Atmospheric Administration National Geophysical Data Center and Space Physics Interactive Data Resource databases. These archives include data from approximately 100 ionosonde stations worldwide, beginning in the early 1940s. Our study focuses on the quality and consistency of ionosonde data accessible via the primary Space Physics Interactive Data Resource node located within the National Oceanic and Atmospheric Administration National Geophysical Data Center and the World Data Center for Solar-Terrestrial Physics located in Boulder, Colorado. We find that, although the Space Physics Interactive Data Resource archives contained an impressive amount of high-quality data, specific problems existed involving missing and noncontiguous data sets, long-term variations or changes in methodologies and analysis procedures used, and incomplete documentation. The important lessons learned from this investigation are that the data incorporated into an archive must have clear traceability back to the primary source, including scientific validation by the contributors, and that the historical records must have associated metadata that describe relevant nuances in the observations. Although this report only focuses on historical ionosonde data in National Oceanic and Atmospheric Administration databases, we feel that these findings have general applicability to environmental scientists interested in using long-term geophysical data sets for climate and global change research.

1. Introduction

Recent attention to human effects on Earth's atmosphere has elevated the importance of the long-term ionospheric data record for understanding upper atmospheric changes. Although changes in Earth's lower atmosphere and in surface temperatures have been well documented (IPCC, 2014; NAS, 2007), changes in land use and corresponding boundary layer effects often complicate efforts to distinguish anthropogenic causes of change from natural ones (IPCC, 2001). Both the ionosphere's location, freeing it from short-term human influences, and the length of the available data record make it an ideal region for evaluating long-term change. A number of researchers have attempted to quantify both long- and short-term processes in the ionosphere, but the results have not always agreed (Akmaev, 2012). This paper summarizes some of the quality issues known to affect the ionospheric data and briefly discusses their implications for scientific studies.

The systematic and coordinated record of ionospheric observations began in the 1940s, based initially on radio soundings. By the 1970s, Doppler radar and other techniques provided additional measurements, and in more recent years, topside soundings from satellites, high-altitude rockets, and digital soundings have added to the amount of data that can be recorded. The record of ionospheric observations is archived by the network of World Data Centers (https://www.ngdc.noaa.gov/stp/iono/ionogram.html). Due to some of the problems uncovered, including those reported in this paper, not all prior data are available. It is currently unclear how problems with data heritage and provenance have been addressed. The World Data Centers, which were established for the International Geophysical Year of 1957–1958, are responsible for the acquisition, storage, and distribution of data, an endeavor not without difficulties. The considerable effort involved in building a comprehensive database in any discipline is frequently increased by inherent quality issues, which are a particular challenge for large data sets. The international data centers offer tremendous opportunity for research, but also have an inherent responsibility to provide uncorrupted data with appropriate supporting information. While this may seem like an obvious requirement of data centers, until the data have been checked, it is not clear that any one data center has fulfilled this requirement.

While considerable effort is often expended toward the technical aspects of storing and distributing large quantities of data, this study highlights the importance of making sure that the data are of sufficient quality to be scientifically useful. Data quality problems can originate from instrumentation limitations, calibration uncertainties, sampling biases, and human-related factors. More recently, a new class of problems seems to be occurring: these problems involve the corruption of data after collection. In some cases, the problems can be omitting collected data or misidentifying data within a database. In other cases, they can involve incompletely describing the data or the presence of biases in the collected data. In previous data handling approaches, data were obtained from the originating scientists and discussions with these experts made it possible to understand data quality and any problems. Common checks of whether data exceed nonphysical limits and are of proper format are insufficient to assure users that data are uncorrupted and scientifically useful. This study highlights some of the problems that can occur in data sets that are not properly checked. Two of the most egregious problems—dropping good data and overwriting good data with erroneous data—are not only sometimes undetectable based on the data centers' quality assurance efforts but might be caused by the data centers themselves or by their data-ingest mechanisms.

Ionospheric data serve a wide range of users, including monitoring of communications, satellite control, and solar activity. Some of the scientific uses for ionospheric observations, including the examination of solar storms and short-term interaction with the thermosphere, require only short-term observations (e.g.,Fang et al., 2014; Lopez-Montes et al., 2015). This paper focuses on both short-term and long-term (climatological) uses of the data, where the consistency and accuracy of the long-term data sets become critical (e.g., Akmaev et al., 2016; Beig & Mitra, 1997; Being et al., 2003; Laštovička et al., 2006, 2008, 2014; Sharma et al., 2015).

For the ionospheric data sets, it is generally accepted that the fundamental measurements are first, of high quality, and second, extend for a considerable period of time. It is also understood that the ionospheric data record is strongly affected by the large variability inherent in the factors influencing the thermosphere-ionosphere-magnetosphere system. Analyses of the data record have produced confusing and even conflicting results for stations located under similar geophysical conditions or even for the same stations, but the definitive source of these apparent conflicts has not been resolved or well addressed (e.g., Danilov, 2008; Danilov & Mikhailov, 1999).

The length of the ionospheric record makes it a useful data set for evaluating long-term changes. Changes in certain upper atmospheric parameters are expected based on simulations of the effects of global climate change. Roble and Dickinson (1989) first modeled the effects of increases in greenhouse gas concentrations on the global mean structure of the upper atmosphere and suggested that some characteristics of the ionosphere were likely to change. The work was followed by Rishbeth's (1990) examination of the possible consequences of the predicted cooling on the ionosphere, Rishbeth and Roble's (1992) modeling study using a three-dimensional general circulation model of the thermosphere and ionosphere, and Fuller-Rowell et al. (1987) discussion of a coupled ionosphere-thermosphere model. The results predicted quite dramatic changes in the height of ionospheric layers, including a lowering of the F_2 peak height, h_mF_2, by 15 to 20 km in response to a doubling of CO_2 and CH_4 amounts in the atmosphere. Other ionospheric parameters, for example, the critical frequency of the F_2 layer, f_oF_2, were found to exhibit only a marginal response.

The initial modeling studies were followed by a large number of investigations looking for signs of possible long-term changes in the historic 60-year record of ionospheric soundings. Overall, these studies indicated that the structure of the upper atmosphere and ionosphere could be changing, although the magnitude of the trends and even their direction remain matters of debate. While early analyses for specific stations (e.g.,Bremer, 1992; Jarvis et al., 1998; Ulich & Turunen, 1997) found decreases in h_mF_2 that were qualitatively consistent with the model predictions, some later and more extensive investigations (e.g., Bremer, 1998, 2001) produced quite mixed results for both h_mF_2 and f_oF_2 with no clear seasonal, solar-cycle, or latitudinal patterns. Recently, Marin et al. (2001) reported mostly positive trends in h_mF_2 at 27 stations in the European and Asian sectors over the last three solar cycles. At the same time, some analyses (e.g.,Danilov & Mikhailov, 1999; Givishvili et al., 1995) suggested relatively strong negative trends in f_oF_2 not predicted by the models.

Another example of contradictory results concerning ionospheric changes is the work of Jarvis et al. (2002) and Mikhailov and Marin (2000) for equivalent data sets. The first effort compiles the results of several authors and reports a negative value for the trend of h_mF_2 at Sodankyla around noon local time (−0.38 km/year). The second work reports, for the same station and same local time, a positive, though small, value of the trend (8×10^{-4} km/year), as well as a negative nighttime value (-15×10^{-4} km/year). Because of the difficulties in quantifying these changes, understanding the nature and best interpretation of the historic data values is essential.

A variety of recent studies have been undertaken which have relied on the development and maintenance of high-quality ionospheric data sets. Dymond et al. (2017) used ionospheric data from the Constellation Observing System for Meteorology, Ionosphere, and Climate(COSMIC) mission to validate modeled slant total electron content at low latitudes from multiple ionospheric models. McNamara et al. (2010) used ionospheric data from CHAMP (Challenging Minisatellite Payload) and the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) instruments to demonstrate that global assimilation models could demonstrate improved large-scale longitudinal variability using their data. Kil and Paxton (2017) used ionospheric data from the Swarm satellites to explain the creation of electron density irregularities in the middle latitudes and their interhemispheric symmetry and possible conjugacy.

The analysis presented here addresses the quality of the long-term observations and the possible effects of quality issues on scientific investigations based on those data. The findings strongly suggest that data quality and consistency play a large role in affecting the trends detected in the long-term data records.

2. Materials and Methods

We explored the quality and consistency of the ionospheric data record by first obtaining the measurements as reported in the Space Physics Interactive Data Resource (SPIDR) database. A number of criteria, including data-reporting time periods, quality flags, and the scale of the measurements, were evaluated to assess the overall availability and quality of the data. In general, the use of qualifying and descriptive letters constitutes per se a first quality control, the process or formulas used to obtain indirect measures (M3000F2, heights, etc.) are clear and widely used, and common regulations (e.g., the URSI Handbook of Ionogram Interpretation and Reduction; Pigott & Rawer, 1972) are employed, all of which assure a very consistent database. Five stations—Boulder, Hobart, Sodankyla, Chilton, and Slough—were selected for more detailed evaluations: these five stations were identified based on the length and apparent robustness of the records. Data from these stations are some of the most often examined and used data in scientific studies. Previously unidentified problems at these stations indicate that the scientific users could have been assuming high quality from the data centers and are not likely to have searched for these problems. It is also likely that problems observed in data from these stations might exist at other stations.

3. Results

3.1. Erroneously Missing Values

A preliminary observation was that the total number of stations reporting to SPIDR has decreased over time. Figure 1 provides an overview of the amount of data available in SPIDR, showing the number of stations reporting for each month. The dip in 1972 cannot be explained, nor is an explanation apparent for the three dips observed in the 1990s. It is presumed that these data were collected and perhaps exist somewhere but are not currently available from the world data center. The data may be described as erroneously missing

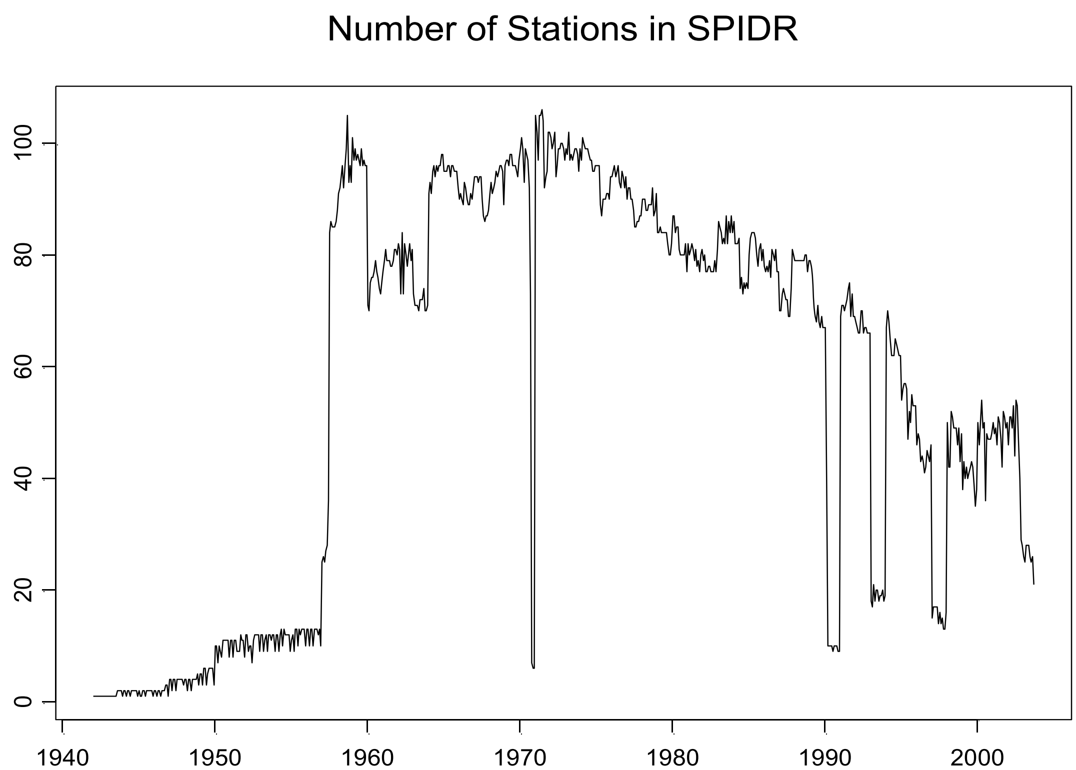

Figure 1. The number of stations reporting data to SPIDR plotted as a function of time. The dips in 1972, the 1990s, and the early 2000s are not understood. The problems of data dropout were pointed out to the data center; it is not clear whether the missing data were reconstituted appropriately, whether the data have been permanently lost, or whether the data were inappropriately overwritten.

if they were collected, are of reasonable quality, and are not available from the data centers. Because of the difficulties inherent in monitoring, a scientific researcher might not suspect that the values are erroneously missing if a station does not have data for a year or two. Because of this reality, the problem of missing values in the data center records could remain unidentified and not be addressed or corrected. The recent fall-off in the number of stations reporting is not understood and does not correspond to the number of known stations collecting data. This fall-off might therefore indicate erroneously missing data from the data center. Until this problem is addressed, it is not clear whether it is due to data ingest problems, the decision of originating sources to stop providing their data, or other issues. Clearly, scientific inquiries are limited not by the lack of good data but by the lack of good data available through the data centers. For many studies, the most recent data are the most valuable, and therefore, even a delay in getting data into the data centers can hinder scientific studies.

Furthermore, a number of missing values were observed in the data record, suggesting that some stations did not report all of the observations. Data were found to be preferentially missing in both high-value and low-value situations. Other missing values were found to be associated with systematic time periods.

3.2. Underreporting From Stations

Inspection of the data records existing in SPIDR also indicates systematically missing values in many of the data records. Since the 1990s, data have been automatically ingested into SPIDR. For each site's data records, we plotted an “*x*” if a value was present and plotted no symbol for missing values. A sample of these results is shown in Figure 2 and indicates that missing values often occur in regular patterns. In the example below, the data gaps correspond to header changes that were being applied to the Monday to Friday data. The problem has been traced down and is attributable to a human error and an inflexible data ingest system located at the SPIDR main node. Still, most of the past data are believed to be irrecoverable. While the identified human problem has been fixed, it is not clear whether such problems will occur in the future, unless efforts are made to search for erroneously missing data.

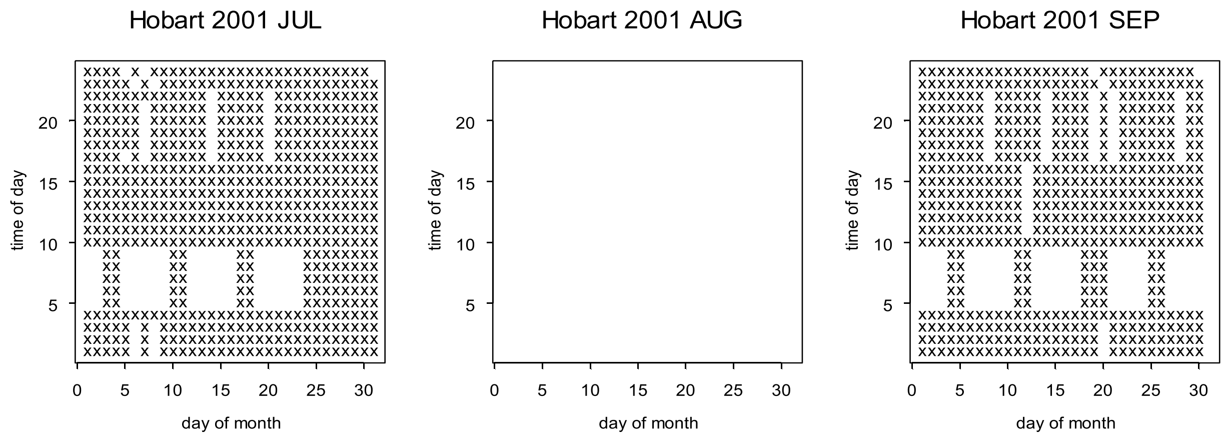

Figure 2. The f_oF_2 data values present in SPIDR are marked with an "x"; missing data are indicated by the white areas and are observed to occur in regular patterns. The data missing for the entire month of August exist, but are not in the SPIDR database. The data missing periodically between 5 UT and 10 UT for periods of five consecutive days exist but are not in SPIDR because of a combination of data ingest problems and human error. The human error could be linked to an individual working Monday through Friday with weekends off. An apparent vacation came at the end of July 2001, along with the noticeable three-day weekend in September. This problem continued for several years but has since been resolved.

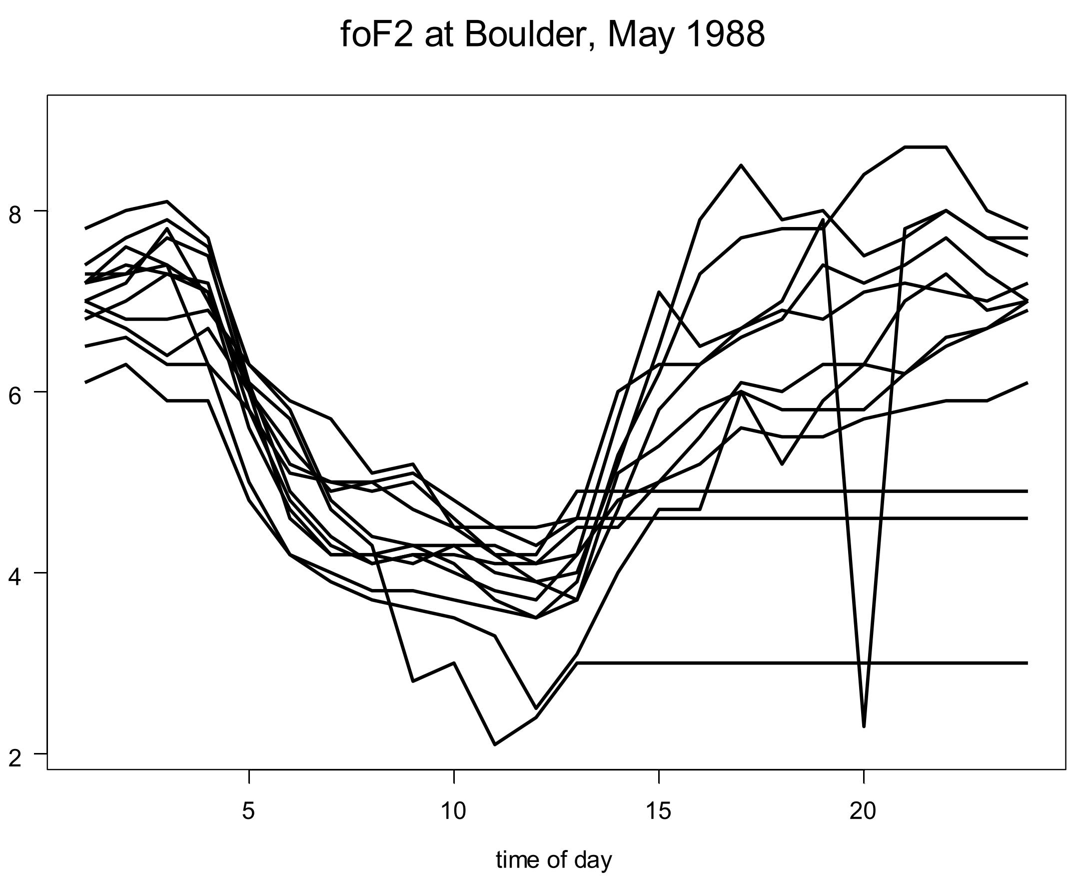

Figure 3. The first 15 days of f_oF_2 hourly data from Boulder are plotted as a function of time of day. Most days reflect a clear and well-understood diurnal cycle. The horizontal lines for the afternoon of three of the days do not indicate missing data, but rather repeat values observed in the files downloaded from SPIDR. There is also one day with a single low value at hour 20. The repeat values are not physically realistic and are likely an artifact of the data treatment at some stage in the processing.

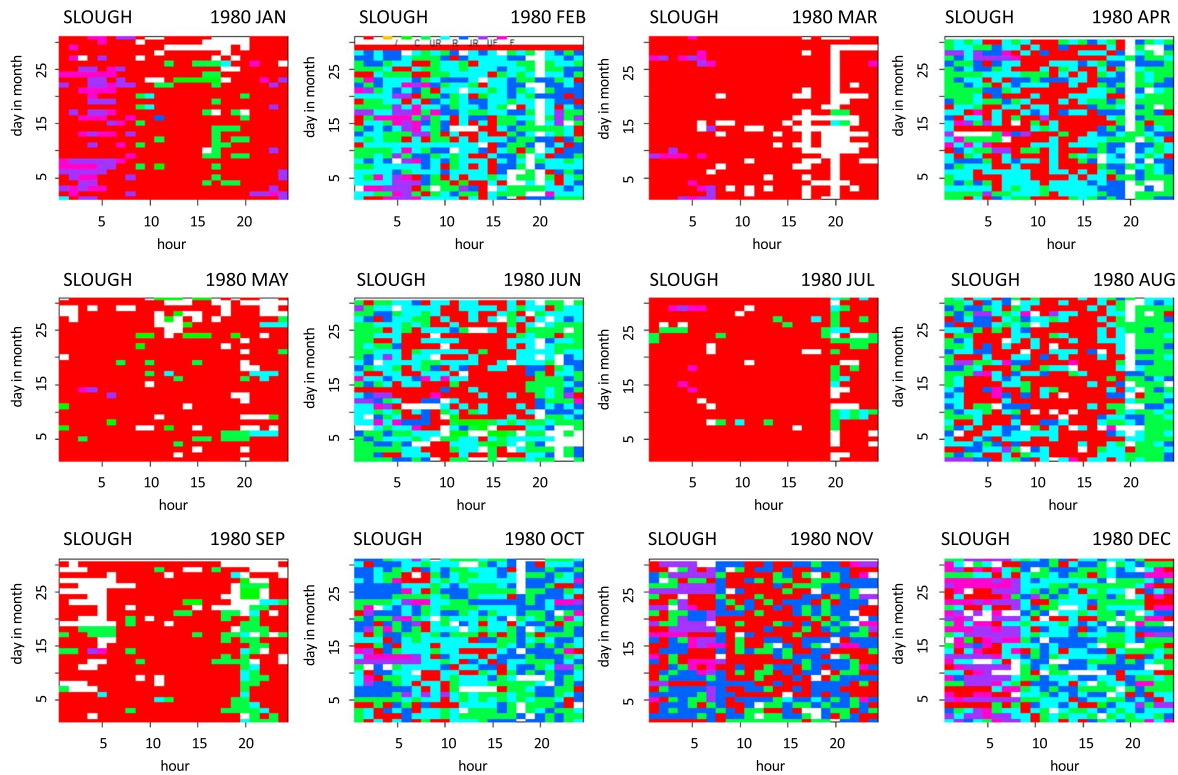

Figure 4. Different qualifier/descriptor pairs are marked by different colors for Slough, 1980. (The qualifier descriptor pairs match as follows: red “ ,” orange “ /,” dark green “UR,” light green “C,” light blue “R,” dark blue “JR,” purple “UF,” and pink “F.” The changes in the types of qualifiers/descriptors used indicate that the information is very dependent on the particular person or program on the task for that month.

As shown in Figure 2, data are missing for the entire month of August 2001. This entire month of missing values is not an isolated occurrence, and the cause remains unclear. The fact that data exist through midnight universal time (UT) on the last day of July and begin again at 1:00 UT on the first day of September indicates that quite possibly the data were collected, but not successfully recorded at the data center. Such missing months, with data through midnight of the prior month and starting at 1:00 UT on the following month, are common in the five sites examined and likely are due to file management problems either at the originating source of the data or at the data center. It is not always clear which of the missing data are erroneously missing.

For the five locations considered, between 10 and 40% of the data were found to be missing, a range that does not agree with what station managers were reporting for collection. Some of these data gaps can easily be screened and inquiries can be made of the stations to assure collection of the data. However, this inspection and inquiry process must take place early because stations do not always maintain their own copies of the data, under the belief that the data are securely stored with the data center. The existence of these gaps and missing values suggests that having scientists and data users involved in regularly examining the recorded data is essential for ensuring a high-quality data record.

3.3. Repeated Values

In-depth evaluations of f_oF_2 values indicate that an individual data point may not always reflect a unique and realistic measurement, and the data quality control flags did not indicate that the data were of poor quality. For example, some measured values appear to be repeated for a number of hours. Such data sequences do not reflect the expected diurnal cycle of f_oF_2 (see Figure 3). The repetitions were observed to occur at all five stations, although their occurrence was found to be inconsistent. A single value is sometimes repeated for a considerable portion of the day. While some repeat values are expected, their preponderance of occurrence in the data records is unlikely to be physically real. The inconsistent occurrence of the values poses serious consequences for scientific studies, particularly those focusing on the short-term variability of the

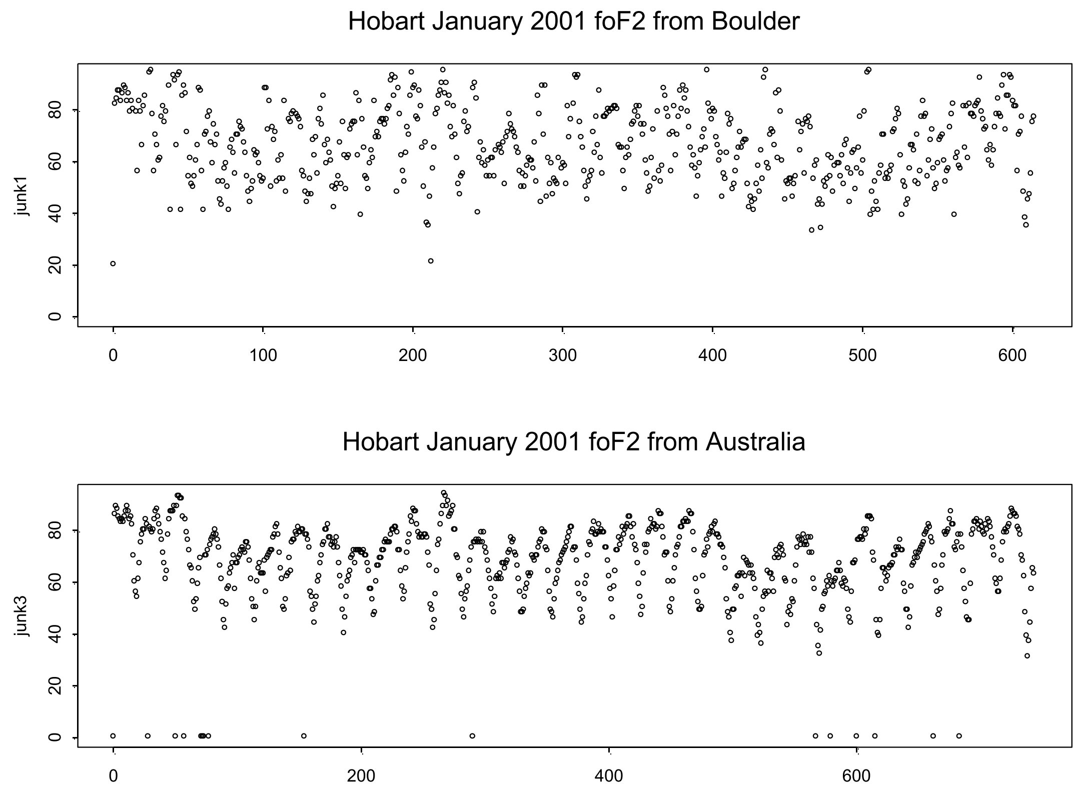

Figure 5. January 2001 time series of f_oF_2 as downloaded in 2003 from the Boulder SPIDR and from the Australia SPIDR. The data records were found to differ dramatically.

ionosphere. For instance, a case study of the ionospheric response to a geomagnetic storm could offer a wrong picture of the system if repeated values are not eliminated, as will occur with a study of the diurnal variation. The effect of this problem could be especially acute for empirical models like the International Reference Ionosphere (Bilitza, 2001; Bilitza et al., 2017) or the STORM model (Araujo-Pradere et al., 2002; Araujo-Pradere et al., 2003), if an adequate quality control of the data is not considered.

3.4. Descriptor and Qualifier Flags

The ionospheric data can be flagged with 10 qualifiers and 22 descriptors by the originating science center (see, for example, http://www.sws.bom.gov.au/World_Data_Centre/2/8/1). The application of quality flags assigned to the data values also raised serious questions about the measurements. In Figure 4, each qualifier/descriptor pair is represented by a particular color. Certain pairs were used extensively in some months, and then not used at all in a consecutive month. These patterns indicate that the use of data qualifiers and descriptors is subjective: it becomes a function of the individual who processes the ionospheric parameters from the raw ionograms, and this occurred before the data were provided to SPIDR. The challenging nature of ionogram interpretation still requires both scientific judgment and scientific qualifiers; we point out how using qualifiers blindly to screen data could result in some unexpected consequences for scientific studies. These changes ultimately limit the usefulness of both the data identifiers and the data.

3.5. Database Problems

Other extremely serious problems emerged during the evaluation of the data. The SPIDR databases are supposed to mirror each other, but the example below indicates that this mirroring is not always the case. The January 2001 data for the Hobart station as downloaded from Boulder SPIDR and from the Australia SPIDR are shown in Figure 5. At the time of the download, the data records were dramatically different, and it was not clear which was correct. One of the two data sets was recently overwritten to match the other: if the wrong data sets were overwritten, the results could be disastrous for analysis, and though it is likely that the Australia SPIDR had the correct values for Hobart, there is no way of

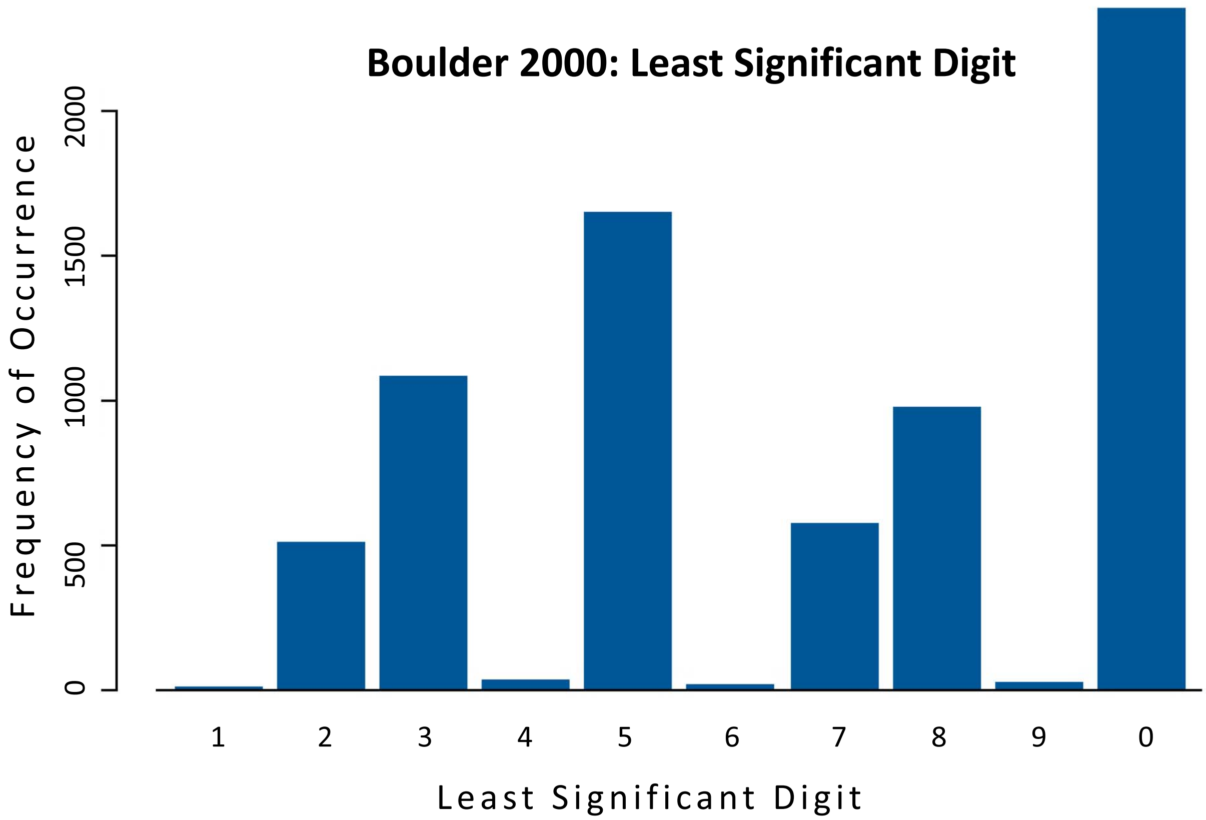

Figure 6. Frequency of occurrence of numerals reported as the least significant digit associated with the measurement. Certain numbers, including 0 and 5, seem to occur preferentially. For example, 7.5 and 7.0 were observed much more often than 7.1 or 7.4. This lack of random distribution is unexplained by the instrumentation and may indicate a lack of precision or possibly a corruption of the data.

determining which data set was correct without obtaining the original ionograms. These types of issues further support the necessity of involving both scientists and data users in the archival and quality assurance process.

Consultations with Phil Wilkinson, the originating scientist, indicated that the data downloaded from Hobart were the correct data. Two years later, the data from the Boulder website were the same but the Australian SPIDR now had the erroneous data. Fortunately, the correct data are still available from Australia because of their internal back-up systems. The correct data can be obtained from Phil Wilkinson on request.

3.6. Technology Changes

Other issues present in the ionospheric data were relatively minor. Changes in technology have allowed more significant digits to be recorded, but the additional output can be difficult to interpret. The frequency of occurrence of the least significant digit is shown in Figure 6 and suggests that certain numbers occur preferentially. This phenomenon has not yet been explained.

3.7. Effects on Scientific Investigations

Recorded monthly time series for the ionosphere for different times of day are presented for Slough in Figure 7. Annual and seasonal averages were created from the hourly data available for each time of day as labeled. Ideally, these time series should be able to be evaluated for trends, but odd points at the end of the record can significantly impact the trends derived. This power of individual points, sometimes referred to as “statistical torque” (for a detailed explanation see, for example, Weatherhead & Andersen, 2006), stems from the fact that regression analyses use the square of the distance from the fit line: if points at either the beginning or end of the record are significantly different, the trend results can be dramatically affected. An

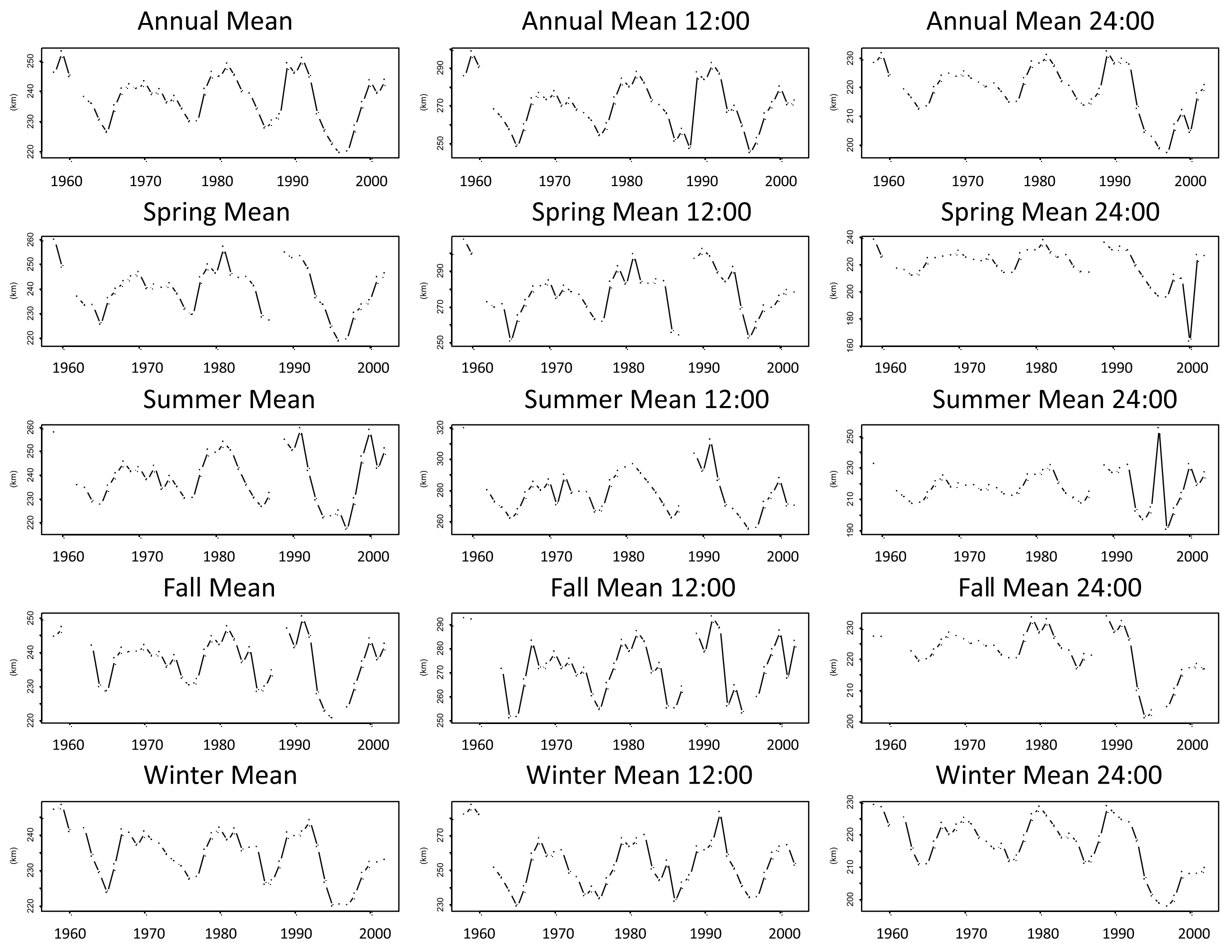

Figure 7. Monthly time series of h_mF_2 from Slough are plotted for different hours of the day. Trend analysis is complicated by the anomalous values at the end of the records. The unusually low values observed at the end of the time series coincide with instrumentation changes. The unusually high values in the first few years of operation are not fully understood and could be real. These values dominate any trend results and may or may not represent a systematic long-term change in the atmosphere.

example of this statistical torque is shown in Figure 8, where low values at the end of the time series strongly affect the derived trends. The effect of these points on the time series analysis highlights the necessity and relevance of understanding most recent digitized data.

One year of autoscaled Standard Archiving Output data products were acquired from NGDC servers and 30-day seasonal medians were generated, centered at each solstice and equinox. An analysis of simultaneous f_oF_2 observations from two co-located instruments at Wallops Island is shown as a function of local time in Figure 9. Dynasonde data are shown as black circles and digisonde data are shown as red triangles. The mean Kp index did not exceed 3.0 for any of the time periods. During each season, the median dynasonde values are regular and exhibit the expected diurnal behavior. The median digisonde values are consistent with the median dynasonde values after midnight for each season, but between noon and midnight there are significant differences between the two curves. In the spring period, the digisonde values drop suddenly around 3:00 PM before returning to the expected values after a few hours. In the fall period, the digisonde values exceed the dynasonde values from noon to approximately 3:00 PM. There is also a sudden drop in the digisonde values in every season, beginning around 6:00 PM and lasting from 2 hr (winter) to more than 8 hr (spring). Section 3.8 provides an examination of an ionogram trace at Wallops Island during these times along with a possible explanation for this behavior.

Seasonal median h_mF_2 values from both instruments are shown in Figure 10. The estimated climatological h_mF_2 from the International Reference Ionosphere model is added as the dashed blue line. The median

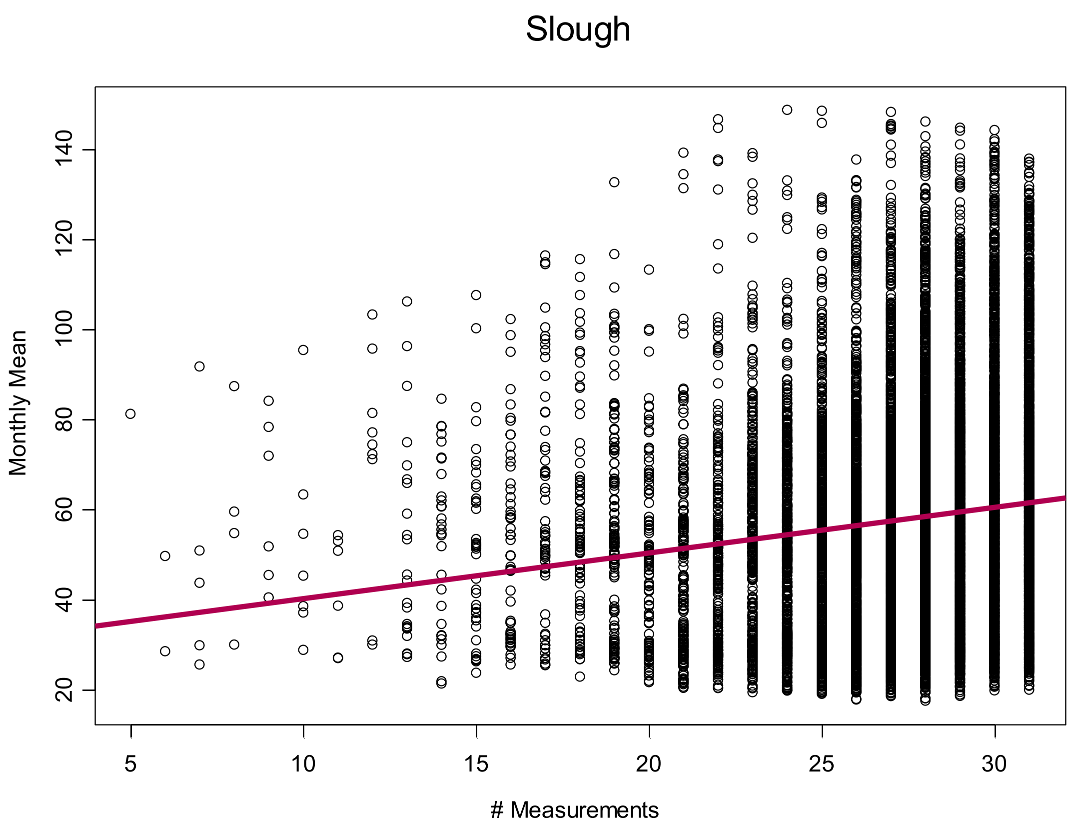

Figure 8. The monthly mean for each of the 24 hr in a day is plotted versus the number of available measurements for Slough. Months when more measurements are available have a higher monthly mean. When capture rates for individual months are high, the monthly mean appears to be generally higher—often by as much as 50%, implying that the months with low capture rates that occurred were months that dropped out low values preferentially. Normal statistics would assume that missing data were randomly missing, which is not the case here.

dynasonde values generally follow the International Reference Ionosphere estimated h_mF_2 very well. However, since h_mF_2 values are estimated using ARTIST, the Automatic Real-Time Ionogram Scaler with True height (Reinisch et al., 1983) autoscaled value of f_oF_2 values (Leo McNamara, personal communication, 8 January 2018), deviations in the digisonde h_mF_2 occur in the same regions as the largest digisonde f_oF_2 deviations, between 5:00 PM and midnight. The shaded green area at the bottom of each plot shows the absolute difference between the dynasonde and digisonde h_mF_2 values. Since the ionospheric *e* folding scale height is around 45–50 km at h_mF_2 altitudes, a horizontal dotted line is added at 50 km (see right axis) to show that the altitude difference between the two data sets achieves the ionospheric-scale height value in the spring, summer, and fall seasons. The digisonde data are systematically low from dusk to midnight and the errors are physically significant. Use of the digisonde data for any long-term study would bias the results, so care should be taken to evaluate data for such errors.

The findings emphasize that data quality significantly affects the analysis of long-term time series. Changes in instrumentation causing shifts in environmental data record or high or low values at the beginning or end of the time series may have particularly strong implications on any derived trends. Past studies (Okada et al., 2003; Weatherhead et al., 2005; Weatherhead et al., 2017) have indicated that an improved understanding of data quality issues is necessary before trends can be determined with any accuracy. Free et al. (2002) demonstrate with sonde data that shifts in the data are difficult to identify, problematic to quantify, and directly impact derived trends, with multiple reasonable approaches giving vastly different results. The observed issues in the ionospheric record and large range of derived trends reported in the literature mandate that data quality must be addressed before trends are derived. Failure to address issues such as repeated values and changes associated with new technologies is likely to result in trend estimates that are not wholly accurate.

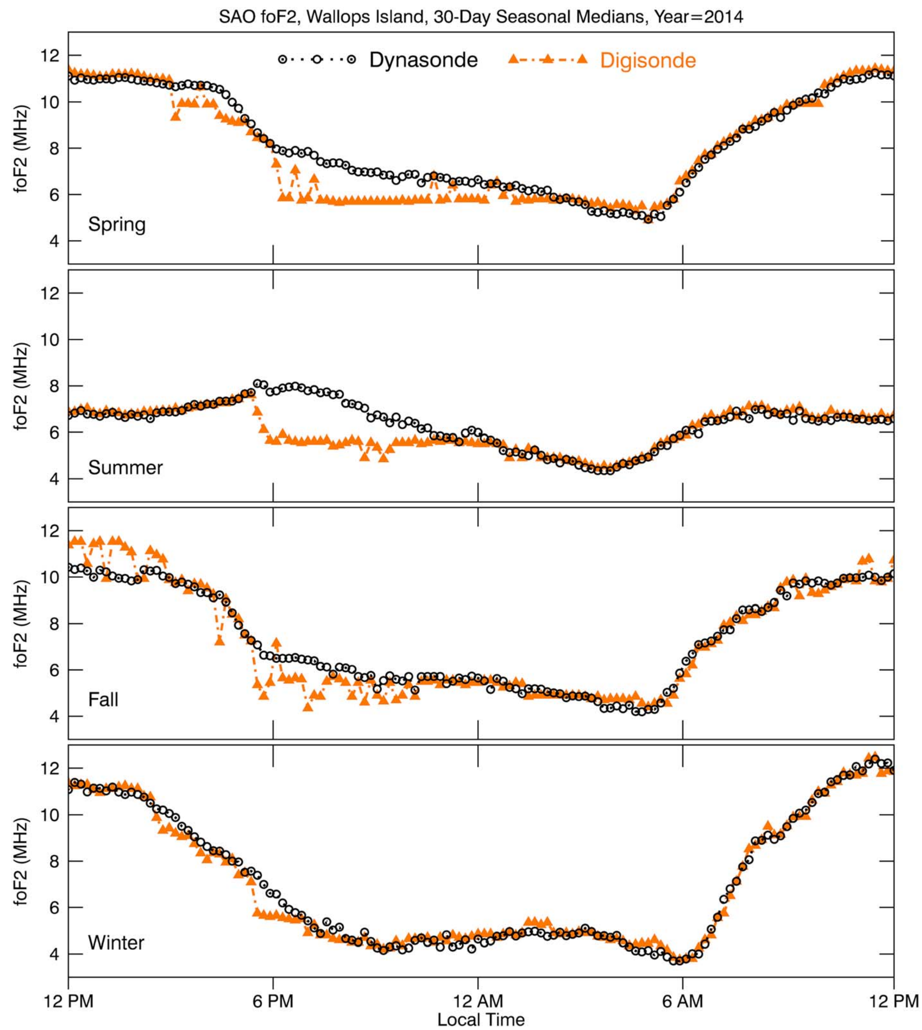

Figure 9. Seasonal median f_oF_2 observations from Wallops Island in the year 2014, from two co-located bottomside sounders. Each time period is centered at an equinox or solstice and spans 30 days. Dynasonde data are shown as black circles and digisonde data are shown as red triangles.

3.8. Example of a Digisonde Ionogram From Wallops Island

An examination of the ionogram traces from the digisonde (WP937) at Wallops Island shows that ARTIST autoscaling of the data routinely wrongly identifies f_oF_2 during the time intervals where the f_oF_2 (and h_mF_2) have gaps in the observations because the analysis ignores the data to the right of the gap. What appears common to these cases, as shown in Figure 11, is a gap in the frequency range coupled with a weak ordinary wave at frequencies above the gap. ARTIST is unable to identify the rest of the ordinary wave and settles for a lower f_oF_2 value at the beginning of the frequency gap—hence the repeated values. The low values of f_oF_2 shown in Figure 9 then translate into the low values of h_mF_2 shown in Figure 10.

This problem always results in f_oF_2 values that are lower than would have been derived with a more complete analysis. The tendency toward lower f_oF_2 identifications by using ARTIST will introduce a false bias in the resulting data.

4. Discussion

The problems described in this paper underscore the need for careful quality control of the data before building models or publishing data-based scientific papers. Problems of this kind affect results describing the

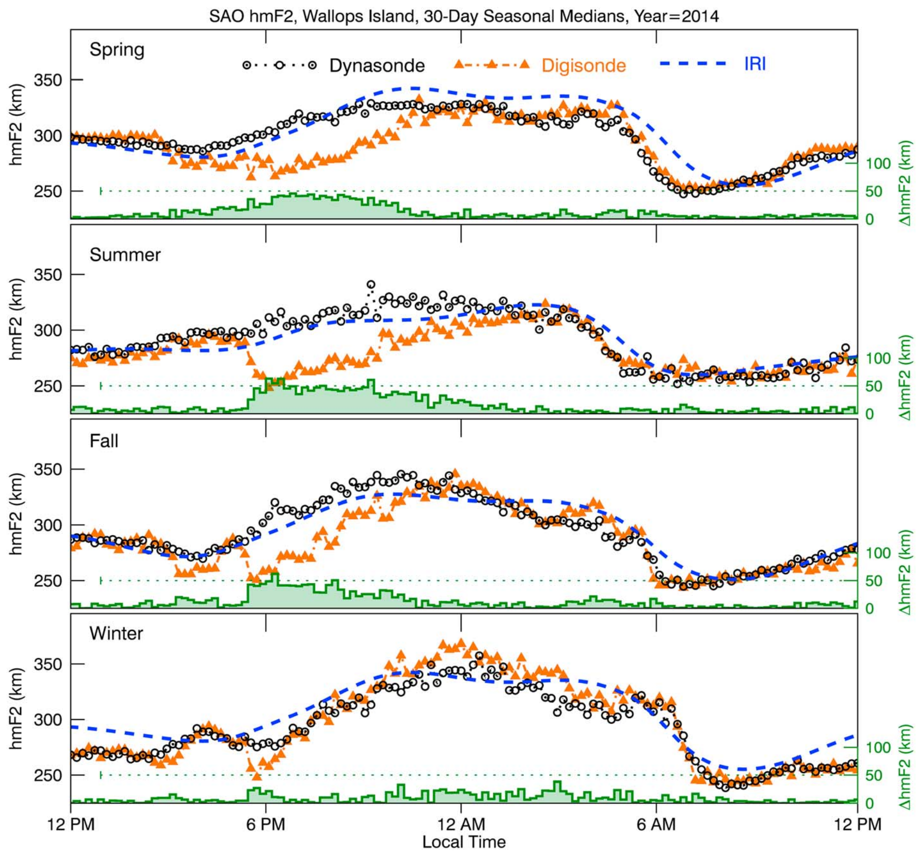

Figure 10. Seasonal median h_mF_2 values from Wallops Island in the year 2014 from two co-located bottomside sounders. Each period is centered at an equinox or solstice and spans 30 days. Dynasonde data are shown as black circles and digisonde data are shown as red triangles. Estimated climatological h_mF_2 from the International Reference Ionosphere (IRI) model is shown as the blue dashed line. The right axis and shaded green areas at the bottom of each plot show the absolute difference between the digisonde and dynasonde h_mF_2 values. The horizontal dotted line is added from the right axis at 50 km as a reference.

ionospheric climatology and could be even worse for studies about the storm time response of the ionosphere and the determination of long-term trends. Models of ionospheric response to geomagnetic storms rely directly on the quality of available data; problems in the data carry straight into these models including biases and larger uncertainty due to erroneous, repeated, and missing observations. To be more specific, the scientific community has used the World Data Center ionospheric database to support innovative research, including studies of both short- and long-term processes (e.g., Araujo-Pradere et al., 2004; Araujo-Pradere et al., 2005; Jarvis et al., 2002; Marin et al., 2001), as well as case studies of individual disturbances, that is, plasma bubble descriptions (Shiokawa et al., 2015), and traveling ionospheric disturbances (Lin et al., 2017), ionospheric response during extreme conditions (Burešová & Laštovička, 2017; Habarulema et al., 2017), and modeling of various purposes (Hernández-Pajares et al., 2017; Liu et al., 2017). Because issues with the quality of the data can substantially affect the outcome of the analyses, feedback from users that are conducting original research based on the data is one of the best ways to detect and possibly correct these issues to decrease their prevalence in the data record. Researchers using the data for scientific investigation are more likely to detect details—often associated with their specific area of interest—that tend to escape to a less meticulous or less intentional inspection of the data. Frequently, quality issues found in the database have been discussed and fixed, which contributes to database improvements. Overall, the way in which the scientists and managers approach data can provide a useful perspective of a record's quality.

Data quality problems are not unique to the ionospheric data set described in this paper. Of particular concern in this set of studies are the idea that systematic problems may be caused by the data archiving

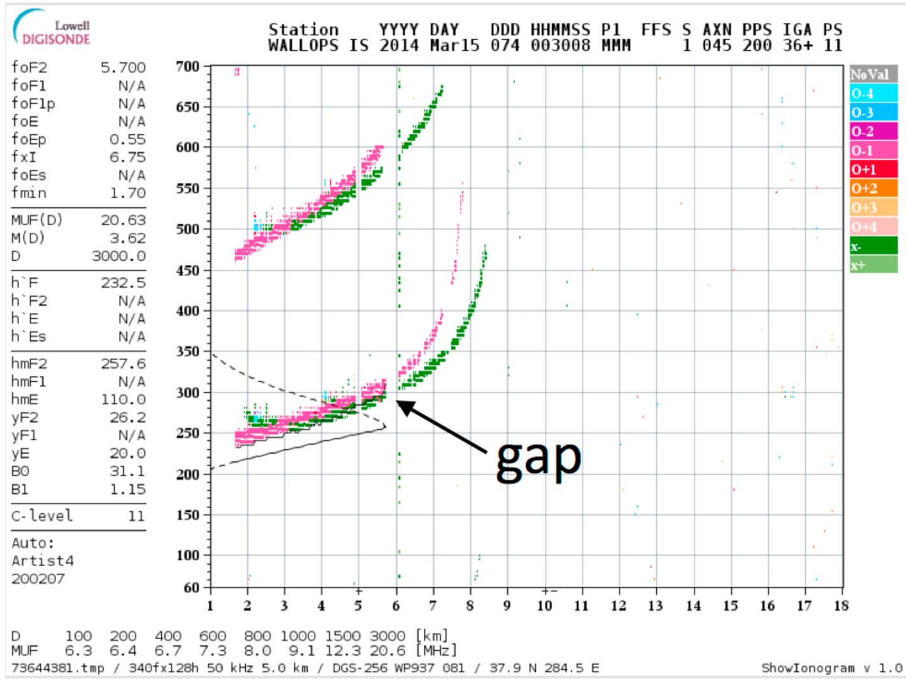

Figure 11. ARTIST autoscaling of data at Wallops Island shows that the autoscaling routinely misidentifies f_oF_2 during the time intervals where the f_oF_2 (and h_mF_2) are systematically low with respect to analyses that include the full signal, including data to the right of the gap.

software and the incorrect scientific and operational conclusions that can result from use of the corrupted or flawed data. Evans et al. (2017) identified inconsistencies in the ozone data downloaded from two different data centers; the cause of the apparently erroneous data appears to be a reprocessing error by the data center. The clear need is for scientific oversight to assure that the data are maintained at a high level of quality. Automated reports on data sent to the originators of site-specific data can help assure that data corruption does not take place. This is analogous to comparing counts of data packets sent and received as a common check for data transfer. Overall, a closer connection between data providers with the goal of developing systems to assure that data quality maintenance and understanding is needed.

5. Conclusions

Ionospheric data provide unique and critical information for understanding both the short-term response of the Earth to solar variability and for evaluating long-term changes in the Earth system. Tremendous effort went into the collection of the ionosonde data with international coordination of acquisition, calibration, and validation efforts. The length and completeness of the ionosonde observations, independence of observing sites, and care taken with the original data collection make the data unique and valuable for a wide range of studies.

This study examines both long-term records and modern side-by-side comparisons. The work reveals some significant concerns about the quality of the records that warrant additional investigations. Some of the identified problems along with an estimate of the magnitude of the potential impacts are presented as examples, although a comprehensive evaluation of the extent of the problems is beyond the scope of this study. Given the fiscal limits of our ability to carry out an exhaustive inventory of the data, it is important and urgent to note that in examining limited sets of data from over 80 different sites, we found that every one of these sites exhibited the behavior that we have described in this work. We note that, as far as we can ascertain, these problems did not exist when the observations were made nor were they present when these data were delivered for permanent archive to the data centers. Clearly, this is an urgent problem; we must ensure that no further bad archives are produced because it is from these archives that the scientific community draw data for analysis. The authors can be contacted on ideas for improved data quality.

Additional problems may be uncovered with further examination. The long-term data sets—some dating back to the early part of the twentieth century—show inconsistencies that can affect scientific conclusions. For example, the application of qualifiers and descriptors are irregular both from station to station and within a single station. More problematic is that some data appear to be corrupted with good observations potentially removed or replaced with erroneous data. The problems imply that the data might not be useful in their current state for addressing some of the scientific applications for which the data might otherwise be uniquely appropriate.

Some of the problems identified may be capable of being corrected if addressed immediately, while original recordings of the observations may be available; other problems will require in-depth understanding of instrument characteristics and calibration. The extent to which the data issues affect the results depends on the type of analysis. Long-term studies, for example, will be most substantially affected by changes over time in the quality of the measurements. Identification of potential problems with the data can help assure the scientific conclusions based on the data including estimates of errors, given the uncertainty on the data quality. We offer this study as a first step toward a more complete evaluation of the quality of ionospheric data sets.

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